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Aridity-induced Miocene canyon incision in the Central Andes

F.J. Cooper¹, B.A. Adams², J.D. Blundy¹, K.A. Farley³, R.E. McKeon^{3,4}, A. Ruggiero⁵

¹*School of Earth Sciences, University of Bristol, Bristol, UK*

²*Department of Geosciences, University of Tübingen, Tübingen, Germany*

³*Department of Geological and Planetary Sciences, California Institute of Technology,
Pasadena, CA, USA*

⁴*Department of Earth Sciences, Dartmouth College, Hanover, NH, USA*

⁵*BHP Billiton, Copper Exploration, Las Condes, Santiago, Chile*

ABSTRACT

The relationship between the rise of the Andean mountain chain and the onset of aridity on its western margin is poorly understood. Canyon incision on both the eastern and western flanks of the chain is interpreted generally as a direct response to increased rock uplift, but may equally have been the result of climate change. Here we record some of the oldest canyon incision on the western Andean margin by tracking the downward migration of the local water table using (U-Th)/He hematite geochronology on vertical drill-core transects. Our data constrain the incision history of the Quebrada de Parca canyon from around 16 million years ago to the present day. The erosional and topographic response of the Quebrada de Parca river suggests that incision was induced by a switch to a more arid climate in the middle Miocene, which reduced regional precipitation and river discharge. Geomorphic analysis of the modern river suggests that the Central Andes have gained only ~700 m of elevation since incision began, and had therefore reached at least 50% of their

current elevation by middle Miocene time. We thus conclude that the onset of aridity at ~16 Ma occurred subsequent to the main Andean uplift.

INTRODUCTION

With an average annual rainfall of $<50 \text{ mm yr}^{-1}$, the western margin of the Central Andes is one of the driest places on Earth. Today, this hyperarid climate is primarily controlled by upwelling of the cold Pacific Humboldt Current, but it may have been intensified by the rain shadow created by the rise of the $>2.5 \text{ km}$ -high Andes mountains since late Oligocene–early Miocene time (e.g. Dunai et al., 2005; Hartley, 2003; Houston and Hartley, 2003; Rech et al., 2006). Questions remain regarding how and when uplift occurred, and how it relates to the onset of aridity. Lamb and Davis (2003) proposed that this extreme topography could result from a positive feedback mechanism whereby increasing aridity promoted rock uplift by reducing the sediment flux to the subduction trench and enhancing the shear stress at the plate interface. This idea is consistent with slow and steady models for Central Andean uplift (e.g. Barnes and Ehlers, 2009; Evenstar et al., 2015), but at odds with suggestions of a more rapid and recent late Miocene uplift history (e.g. Garzzone et al., 2008; Jordan et al., 2010), which would have occurred long after the change in climate.

Discrimination between these models requires precise constraints on the timing of both Andean uplift and the shift to a drier climate. Andean rivers within deeply incised canyons that drain the flanks of the range provide an ideal opportunity to do just this because they record regional changes in the balance between rock uplift and erosion (e.g. Lease and Ehlers, 2013).

Physical and numerical models of landscape evolution (e.g. Bonnet and Crave, 2003; Whipple and Tucker, 1999) suggest that canyon incision can initiate in one of two ways,

each of which is accompanied by an increase in mean elevation (surface uplift). (1) An increase in rock uplift rate, which causes rivers to steepen and incise in order to match the higher rate. (2) A decrease in precipitation, which reduces river discharge, causing rivers to steepen and incise so that they continue to erode at the same rock uplift rate. In both scenarios, fluvial incision causes a downward migration of the water table relative to the surface. Therefore, the position of the water table over time is intimately linked to local river base level.

In this study, we constrain the downward migration of the water table in the Cerro Colorado copper mine on the western flank of the Central Andes and use it to infer the incision history of the adjacent Quebrada de Parca canyon (Fig. 1). We use (U-Th)/He dating of hematite precipitation to track a slow and steady lowering of the water table from ~16 Ma to the present day at a rate of $\sim 10 \text{ m Ma}^{-1}$. Based on geomorphic analysis of the modern Quebrada de Parca river, models of landscape evolution, and correlations with independent studies of rock uplift, climate change, and incision, we suggest that this lowering is a direct response to fluvial incision triggered by a switch to drier climatic conditions in the middle Miocene.

GEOLOGIC SETTING

The Western Andean Slope is one of five morphotectonic units that make up the western margin of the Central Andes (Fig. 1). Characterized by a relatively smooth surface, it is thought to define the limb of a crustal-scale monocline accommodating differential rock uplift of the Western Cordillera with respect to the Central Depression (e.g. Isacks, 1988; Jordan et al., 2010). The slope is covered by Oligocene-Miocene volcanic and sedimentary units and a ~1–10 m-thick layer of alluvial fan gravels that form a regional “bajada” surface along the range front. This bajada records an older fluvial drainage

network cut by a series of younger, deep canyons (quebradas) draining westward to the Central Depression, which is known to have existed since at least the late Oligocene (Jordan et al., 2010 and references therein).

The Western Andean Slope also hosts some of the largest porphyry copper deposits in the world, including our study site, Cerro Colorado. The local geology here comprises volcanic and volcanic-sedimentary andesite, breccia, tuff, and agglomerate of the late Cretaceous Cerro Empexa Formation intruded by late Cretaceous–early Tertiary tonalite, granite, diorite, and quartz monzonite stocks. This sequence is unconformably overlain by two alluvial sedimentary units, the Sagasca and Imagua Gravels, separated by the 19.79 ± 0.12 Ma (2σ) Tambillo ignimbrite. The upper age limit of these gravels is constrained by the $16.20 \text{ Ma} \pm 0.14 \text{ Ma}$ (2σ) Huasco ignimbrite, remnants of which can be found lying directly on the Imagua Gravel to the east of the study site (Blanco et al., 2012 and references therein; Bouzari and Clark, 2002). The Cerro Colorado pit is located on the southern rim of the Quebrada de Parca, a 300-m deep canyon with an ephemeral stream that terminates in the Central Depression (Figs 1 and 3a).

(U-Th)/He HEMATITE GEOCHRONOLOGY

Hematite (Fe_2O_3) is prevalent in the barren “leached cap” of the Cerro Colorado copper deposit (Bouzari and Clark, 2002) and results from the dissolution of iron sulfides, particularly pyrite (FeS_2), by oxygenated groundwater (e.g. Ague and Brimhall, 1989). In the oxic zone above the water table, this process is continuous until all the sulfides are dissolved. Therefore, if the water table is static for any period of time, hematite should show a range of ages reflecting ongoing precipitation. The redox interface at the water table acts as a barrier to this process, with hematite unable to precipitate in the reducing environment below. Any relative lowering of the water table will expose rocks to the oxic

zone, triggering the resumption of precipitation. The depth of hematite precipitation as a function of time can, therefore, be used to track the relative movement of the water table.

We collected nine hematite-bearing samples of altered diorite porphyry from three vertical drill holes in the Cerro Colorado leached cap for (U-Th)/He dating. The primary igneous mineral assemblage in each sample had been largely replaced by sericite and clay, and cross-cut by a network of mm- to cm-wide veins of hematite. We infer that these veins originally contained sulfide minerals that were subsequently replaced in-situ by hematite (see Data Repository DR1).

The (U-Th)/He hematite system (e.g. Farley and Flowers, 2012; Reiners et al., 2014) has a closure temperature of 60–200°C depending on the diffusion domain size of the analyzed hematite. Since the water table resides at ambient temperatures considerably lower than this, we interpret (U-Th)/He ages as recording the time of hematite precipitation. All samples were analyzed in the Caltech Noble Gas Laboratory (see Data Repository DR2).

The nine samples yielded 33 hematite precipitation ages ranging from 31 to 2 Ma, defining two distinct age-elevation relationships (Fig. 2 and Table DR6). Between 31 and ~19 Ma there is no correlation between age and elevation, reflecting a prolonged period of water table stability. We interpret this as a time of slow, sustained aggradation of alluvial material forming the Sagasca Gravel. At ~19 Ma, the area was covered by the Tambillo ignimbrite, but the continued absence of an age-elevation correlation suggests that this event had no discernible effect on the water table. After the ignimbrite was emplaced, alluvial material continued to accumulate for another ~3 million years, creating the Imagua Gravel, until it was covered by the Huasco ignimbrite at 16 Ma.

The range in ages at a given stratigraphic position makes it difficult to precisely pinpoint the end of water table stability, but between ~18 and 15 Ma, there is a change in

the age-elevation relationship where the hematite ages begin to decrease steadily with elevation. This trend continues to the youngest sample at 2 Ma and implies at least 13 million years of rock movement relative to the water table. The y-intercept of this trend, where the (U-Th)/He age is zero, lies at 2300 m, coincident with the elevation of the modern water table from drill hole data and the floor of the Quebrada de Parca, suggesting that water table lowering has continued to the present day.

Assuming that the water table is directly linked to local river base level, we suggest that this downward migration reflects incision of the Quebrada de Parca. Since the river cuts through the Imagua Gravel at the study site, and through the Huasco ignimbrite upstream, we infer that incision must have started after ~16 Ma, further constraining its onset to a narrow age range around 16–15 Ma. For the remainder of our discussion, we will use the more conservative estimate of ~16 Ma, which means that subsequent incision induced a lowering of the water table at a steady rate of ~10 m Ma⁻¹. While this rate is slow, it is consistent with other fluvial incision rates recorded in the region (~7 to ~20 m Ma⁻¹; Barnes and Ehlers, 2009 and references therein). The spread in ages within each sample could have three possible causes: (1) continuous precipitation of hematite; (2) a geological signal unresolvable by our dataset (e.g. a climate induced reduction in aquifer recharge, a perched water table, or a non-uniform history of water table lowering); or (3) issues with the (U-Th)/He hematite method (e.g. contamination by other U- or Th-bearing phases, or overheating of hematite during He degassing; see Data Repository DR2).

GEOMORPHIC ANALYSIS OF THE QUEBRADA DE PARCA

While the (U-Th)/He results combined with the local stratigraphy constrain the onset of canyon incision to ~16 Ma, they do not elucidate the driver for incision. To do this, we turned to geomorphic observations of the modern Quebrada de Parca river (Fig. 3) to

investigate two possible triggers: (1) tilting of the Western Andean Slope in response to increased rock uplift of the Western Cordillera relative to the Central Depression; and (2) a reduction in mean annual precipitation following a shift to a more arid climate.

The Quebrada de Parca exhibits a concave longitudinal channel profile with an inverse relationship between upstream drainage area and local channel gradient (Fig. 3b). Therefore, to compare the relative steepness of different segments of the river, we use the normalized channel steepness index (k_{sn} , referred to henceforth as channel steepness), which accounts for this co-variation and, in most landscapes, is directly proportional to the rock uplift rate. In a linearized channel profile (Perron and Royden, 2013), the river is clearly defined by a steep lower segment and a shallow upper segment, separated by a convex knickpoint at ~3250 m elevation (Fig. 3c). Such a morphology is often indicative of a dichotomy between two erosion rates where the downstream segment has steepened to set a higher erosion rate while the upper segment continues to erode at a lower rate (Wobus et al., 2006).

A convex knickpoint is also seen in a number of river channels adjacent to the Quebrada de Parca at roughly the same elevation (Fig. 3a). While these knickpoints could be attributed to the presence of an active fault system, there is no obvious candidate for a structure that could control this regional break in topography. The knickpoints would require either an east-vergent thrust or an east-dipping normal fault to produce higher rock uplift rates on the downstream side relative to the upstream side, but geologic maps suggest that the faults in this location are west-vergent thrusts (Sernageomin, 2003). The knickpoints are also not controlled by differences in bedrock as they are found within both plutonic and volcanic rocks alike and do not coincide with any mapped geological contacts.

Local base level in the Central Depression is marked by a concave knickpoint at ~1100 m elevation that also does not correspond to any mapped surface-breaking faults. A seismic study ~50 km south of the Quebrada de Parca (Labbé et al., 2015) suggests that faults at this distance from the Western Andean Slope are minor and buried. Therefore, we see no evidence for a fault system that could control the local base level of the rivers or account for a higher rock uplift rate on the Western Andean Slope relative to the Central Depression. Furthermore, the uniform nature of the Quebrada de Parca linearized channel profile suggests that there has been no significant fault activity between the two knickpoints since ~16 Ma.

LANDSCAPE EVOLUTION MODELING

With no evidence for any faults or geologic contacts controlling the Quebrada de Parca knickpoints, we conducted landscape evolution modeling experiments to investigate the cause of the stepped channel profile. Using the Channel Hillslope Integrated Landscape Development (CHILD) model (Tucker et al., 2001), we created a steady-state landscape with spatially uniform rock uplift and precipitation rates, governed by the stream-power incision model (e.g. Whipple and Tucker, 1999). We then perturbed the topography by applying either (1) a spatially variable, linear upstream increase in rock uplift rate, or (2) a spatially uniform decrease in precipitation rate (Fig. 4 and Data Repository DR5).

Our experimental results demonstrate that a linear upstream increase in rock uplift rate will produce an above-average river concavity (e.g. Kirby and Whipple, 2001), but not a discrete convex knickpoint (Fig. 4a). This suggests that there has been no significant differential rock uplift along the Quebrada de Parca since ~16 Ma. Instead, we find that the stepped morphology of the river can be produced by a spatially uniform decrease in precipitation (Fig. 4b), whereby the river steepens as a convex knickpoint migrates

upstream. We suggest, therefore, that a switch to a more arid climate at ~16 Ma reduced mean annual precipitation, causing the river to steepen and incise in order to keep pace with the existing rock uplift rate (e.g. Bonnet and Crave, 2003). The wave of incision would have started in the lower reaches of the river and migrated upstream until it reached the study site. Therefore, our constraint of ~16 Ma provides a minimum timing for the onset of aridity, and the presence of the convex knickpoint in the river today demonstrates that the landscape response to aridification is still not complete.

A number of previous studies on the western margin of the Central Andes are broadly consistent with a switch to aridity around 16 Ma. For example, Rech et al. (2006) used paleosols to infer a change from semiarid to hyperarid conditions between 19 and 13 Ma. Evenstar et al. (2009) used cosmogenic nuclide exposure dating of boulders on an abandoned alluvial surface to infer that active deposition ceased at ~14.6 Ma due to a shift to more arid conditions, while groundwater-driven supergene mineralization in the majority of porphyry copper deposits is thought to have ended by ~14 Ma (e.g. Bouzari and Clark, 2002; Sillitoe and McKee, 1996). However, others have suggested a much earlier onset of aridity at ~25 Ma, significantly before we see the transition in our (U-Th)/He data (Dunai et al., 2005). Canyon incision on the western Andean margin in northern Chile is generally thought to have started at ~10 Ma (e.g. García et al., 2011; Hoke et al., 2007; Schlunegger et al., 2006), which is later than our data suggest, although Sebrier et al. (1988) suggested an earlier onset in Southern Peru at ~16 Ma.

CONSTRAINTS ON CENTRAL ANDEAN UPLIFT

Our geomorphic observations also allow us to estimate the surface uplift (ΔZ) of the Western Cordillera relative to the Central Depression since ~16 Ma. Using the linearized river profile (Fig. 3c), we projected the trend of the older, upper segment above the

knickpoint towards local base level in the Central Depression and calculated a difference in elevation between the modern base level and the uplifted base level (ΔZ) of 692 ± 65 m (2σ). We find a similar result of 704 ± 55 m (2σ) for the neighboring Quebrada Tambillo (Figs 1b, 3a, and Data Repository DR4). Although our results cannot be integrated over the entire vertical relief of the orogen (they exclude the ~ 1100 m difference in elevation between the Central Depression and the Pacific Ocean), we suggest that the Central Andes must have already attained at least 50% of their current elevation by the middle Miocene, consistent with slow and steady models for Central Andean uplift (e.g. Barnes and Ehlers, 2009; Evenstar et al., 2015; Lamb and Davis, 2003). We thus conclude that the onset of aridity at ~ 16 Ma occurred subsequent to the main Andean uplift.

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FIGURE CAPTIONS

Figure 1. The five morphotectonic units of the western Andean margin and the location of the study site, Cerro Colorado (CC). In this area, the Western Andean Slope is cut by a series of canyons (quebradas), including the Quebrada de Parca, which drain from the Western Cordillera to the Central Depression.

Figure 2. (U-Th)/He hematite geochronology results. From ~31 to ~16 Ma, there is no correlation between age and elevation, whereas from ~16 Ma onwards, ages decrease with elevation at a rate of ~10 m Ma⁻¹.

314

315 **Figure 3.** (a) Digital elevation model of the Quebrada de Parca and Quebrada Tambillo
316 river networks (blue lines) and local faults (black lines; Sernageomin, 2003). Dark blue
317 lines denote channels used for geomorphic analysis. (b) Longitudinal channel profile of the
318 Quebrada de Parca (hillslopes excluded). Local base level is marked by a concave
319 knickpoint at ~1100 m elevation (pink circle). Cerro Colorado is situated above the river at
320 ~2600 m (red star), and a convex knickpoint lies at ~3250 m (green circle). (c) Linearized
321 channel profile in which longitudinal distance is replaced with the integral of upstream
322 accumulation area (χ), removing the effects of channel concavity. The slope of the profile
323 is the channel steepness (k_{sn}). ~700 m of surface uplift (ΔZ) of the Western Cordillera is
324 determined by projecting the upper segment of the river (red dashed line) to the position of
325 local base level and measuring the vertical offset in elevation.

326

327 **Figure 4.** Linearized channel profiles showing landscape evolution model responses. Axes
328 are normalized to maximum values of the initial steady-state river conditions. (a) A linear
329 upstream increase in rock uplift rate (U) increases the concavity of the river but does not
330 produce a discrete knickpoint. (b) A uniform decrease in precipitation rate (P) results in
331 steepening of the river beneath a migrating convex knickpoint. Note that the amount of
332 surface uplift at any position along the river is simply the difference in elevation between
333 the red and blue profiles.

334

335 ¹GSA Data Repository item 2016xxx, DR1 (Sample descriptions), DR2 ((U-Th)/He
336 hematite analysis), DR3 (Channel profile analysis), DR4 (Surface uplift calculations), DR5
337 (Landscape evolution modeling), and DR6 (Hematite (U-Th)/He data), is available online

338 at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or
339 Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 1

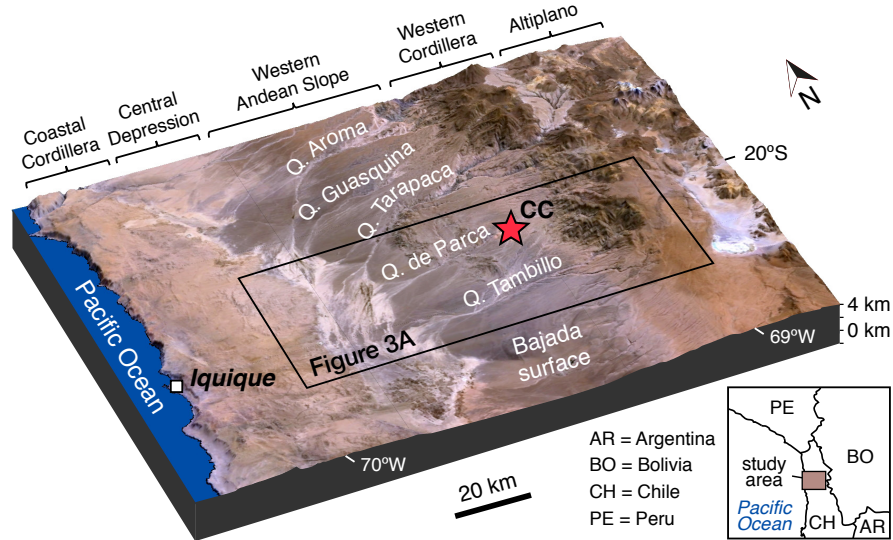


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Figure 2

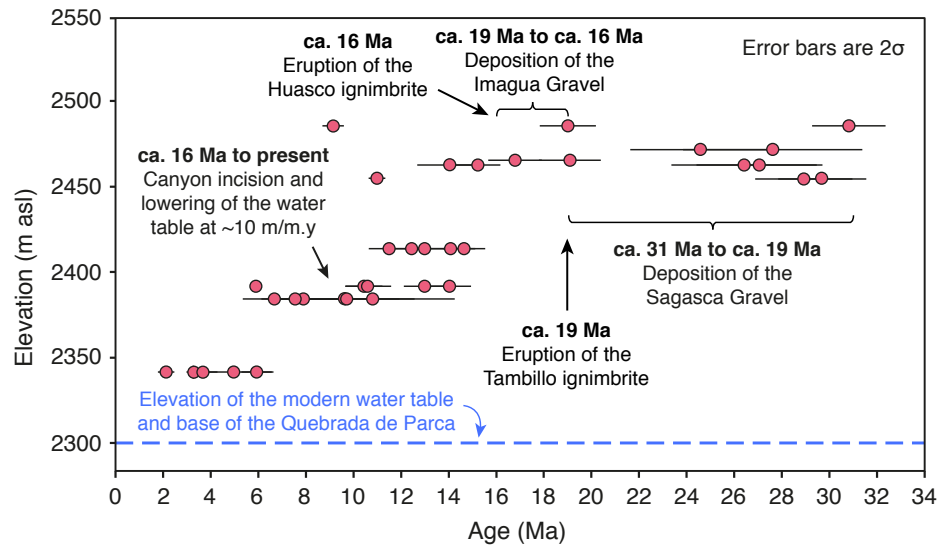


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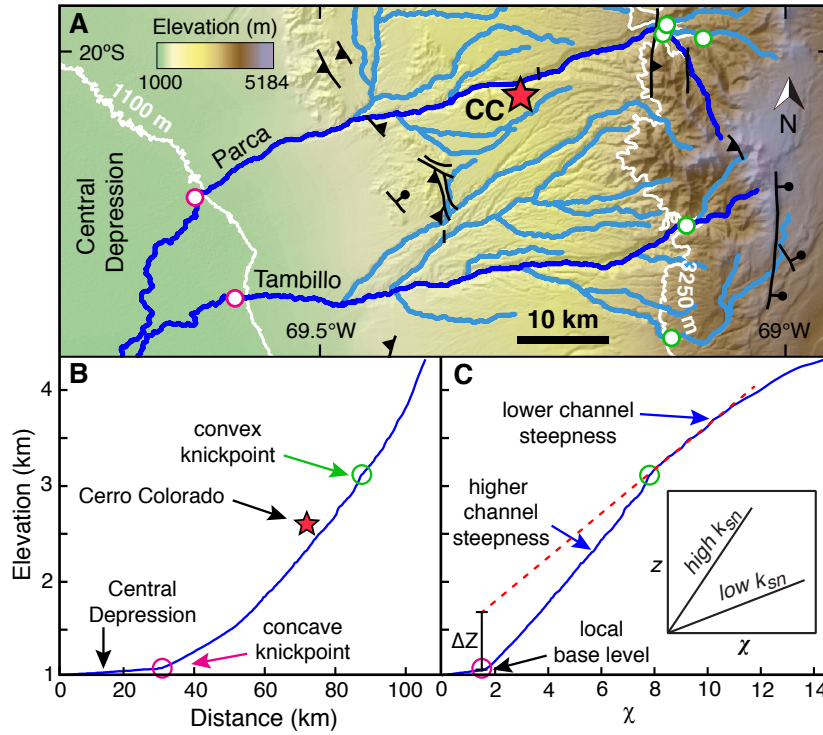


Figure 3. (a) Digital elevation model of the Quebrada de Parca and Quebrada Tambillo river networks (blue lines) and local faults (black lines; Sernageomin, 2003). Dark blue lines denote channels used for geomorphic analysis. (b) Longitudinal channel profile of the Quebrada de Parca (hillslopes excluded). Local base level is marked by a concave knickpoint at ~1100 m elevation (pink circle). Cerro Colorado is situated above the river at ~2600 m (red star), and a convex knickpoint lies at ~3250 m (green circle). (c) Linearized channel profile in which longitudinal distance is replaced with the integral of upstream accumulation area (χ), removing the effects of channel concavity. The slope of the profile is the channel steepness (k_{sn}). ~700 m of surface uplift (ΔZ) of the Western Cordillera is determined by projecting the upper segment of the river (red dashed line) to the position of local base level and measuring the vertical offset in elevation.

Figure 4

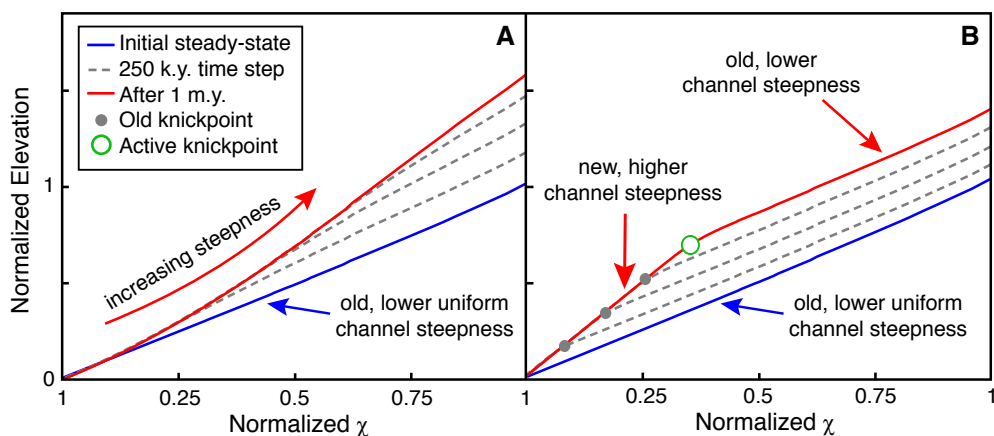


Figure 4. Linearized channel profiles showing landscape evolution model responses. Axes are normalized to maximum values of the initial steady-state river conditions. (a) A linear upstream increase in rock uplift rate (U) increases the concavity of the river but does not produce a discrete knickpoint. (b) A uniform decrease in precipitation rate (P) results in steepening of the river beneath a migrating convex knickpoint. Note that the amount of surface uplift at any position along the river is simply the difference in elevation between the red and blue profiles.